SCHISTOSITY AND SLATY CLEAVAGE.

SOME years since I published a paper on the finite, homogeneous strain, flow and rupture of rocks[1] which contained with other matter a new theory of slaty cleavage and the allied less regular schistose cleavage. Colleagues have lately informed me that this paper is too mathematical for their convenience, and I therefore propose to discuss schistosity and cleavage without mathematics. The result cannot be wholly satisfactory in the nature of the case; nevertheless this presentation will suffice for those who care little about the matter and will make my former discussion easier to those who are more interested. No part of that discussion is really difficult, but the chain of reasoning is unavoidably long and therefore trying to the patience. The general idea to be developed is that the deformation of a solid, homogeneous, viscous, isotropic, not infinitely brittle mass will develop structure in it, on not less than one surface nor on more than four surfaces simultaneously. These structure surfaces will in general stand at acute angles to the direction of the pressure to which they are due and the flattening of the strain ellipsoids will not be normal to the pressure except in a limiting case. The assumptions needful to prove these propositions are almost axiomatic, viz., stresses and strains are of the same order of magnitude; a solid mass opposes deformation by forces which are divisible into those independent of the time rate of straining and those which are dependent on this rate.

[1] Geological Soc. of Amer., Vol. IV., 1893, pp. 13–90. An earlier paper, the structure of a portion of the Sierra Nevada of California, appeared in the same series, Vol. II., 1891, p. 49, and a later one, the finite elastic stress strain function, was printed in the Amer Jour. of Science, Vol. XLVI., 1893, p. 337. A paper on the torsional theory of points may be found in Trans. Amer. Inst. Mining Engineers, Vol. XXIV., 1894, p 130. I may mention in the same connection an essay on distributed faults, U. S. Geol. Sur., Monograph III., 1882, chap. iv.

On the other hand experience must be appealed to in the present state of knowledge to decide whether the surfaces of structure will show diminished or increased resistance to splitting.

This theory differs very radically from the older one according to which cleavage occurs only in heterogeneous masses and is normal to the causative force. It is certainly important for geologists to decide between the two, for the effect of geological forces is chiefly manifested in structures of the kind under discussion. In my opinion joints, slickensides, faults, systems of veins, schists and slates are all closely allied manifestations of force and the true theory of one of them must explain them all. These structures constitute the alphabet of the dynamic record. Upheaval and subsidence will never be elucidated until the history of mountain building can be correctly spelled out.

The term "strain" as applied to a solid body signifies a change in shape or size such as would result from the action of external forces.[1] Acquaintance with two strains only is requisite for the purposes of this paper. One of these will be called "pure shear" or simply "shear," and the other will be called "scission."

Pure shear is the simplest conceivable strain. It involves only a change of shape, and this change takes place only in two dimensions. Nevertheless it presents interesting and important properties. If a cube of any solid be subjected to a uniformly distributed load, acting normally as a pressure on two opposite faces, and is at the same time affected by an equal load acting as a normal tension on two opposite faces at right angles to the first pair, as shown in Fig. 1, it will be elongated in one direction and contracted in the other. Such a distribution of forces will not alter the volume; there will be no change of length or direction in lines perpendicular to the plane of the forces; and lines originally parallel to either pair of forces will remain

[1] Stress is force measured per unit area; or in the case of "bodily" forces such as gravity per unit volume. In the mechanics of elastic bodies stresses are either the external forces which cause strain, or the equal and opposite elastic resistances which the external forces excite in the strained mass.

parallel to them however great the distortion may be. If horizontal edges of the unit cube are extended in the ratio a so that these edges in the strained mass have a length a, then the vertical edges are contracted in the ratio $1a$. It is usual to define the quantity a $1a$ as the "amount" of shear. If the

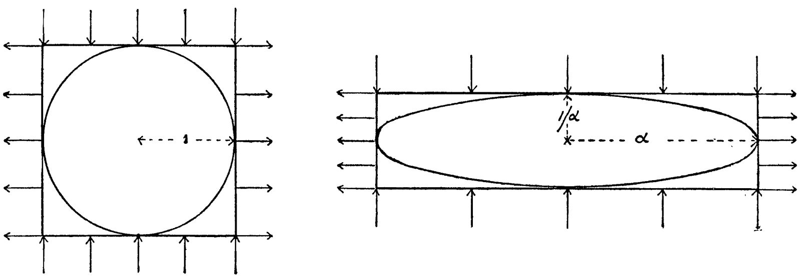

FIG. 1 —Pure Shear.

unstrained cube contained a sphere, this in the strained mass would become an ellipsoid with axes a, 1, $1a$.[1]

Since a is greater than unity, and $1a$ less, there must be radii of the ellipse in the plane of forces which are of unit length, and which are therefore of the same length after strain as they were before. Since the lines perpendicular to the plane of forces are also of unchanged length, it is evident that the circular sections of the ellipsoid pass through the radii of unchanged length in the ellipse. These circular sections of the strain ellipsoid are of as much importance in the theory ot deformation as are the corresponding sections of the ellipsoid of elasticity in the theory so familiar to most geologists of the effect of crystals on polarized light.

All planes parallel to the central circular sections are also circular sections. In the plane of any such section there is no distortion when the strain is a simple shear. Any two such

[1] If the equation of the sphere is $x^2+y^2+z^2=1$, and if x_1, y_1 and z_1 are the values which the same points have after strain, $x_1 = a\ x, y_1 = ya$ and $z_1 = z$. Substituting in the equation of the sphere evidently $x_1\ 2a\ ^2 + a^2\ y^2 + z^2 = 1$, represents the sphere after deformation. The volume of this ellipsoid is $\pi a.\ 1.\ 1a =$ which is also the volume of the sphere.

planes are also at the same distance apart after strain as before, for otherwise the volume of the mass must have undergone alteration which would be inconsistent with the definition of pure shear. Since these planes have the same shape, dimensions and distance apart after strain as before it, there is but one change which they can possibly have undergone, viz., a gliding movement past one another. One may regard the entire ellipsoid as intersected by planes parallel to the circular sections and very close together. Consequently also the process involved in a shear consists solely in the sliding past one another of the thin plates bounded by such sections.[1] A convenient model illustrating the nature of shear is a bit of wire netting. If a piece of such netting is pulled diagonally to the mesh, each of the two systems of interwoven wires is distorted much like the traces of the corresponding system of circular sections in the shear ellipse.

The circular sections must necessarily be planes on which the forces are purely tangential; for if the forces had any normal component whatever distortion would ensue. Now it is easy to show that in any shear, however great, the load (or the force per unit area multipled by the area) is exactly the same for every central section passing through the mean axis.[2] In general this load is inclined, so that it has both a component perpendicular to the given section and also a second component tangential to it. On the two axial sections of the ellipsoid, (*i. e.*, the central sections perpendicular to the greatest and least axes) these loads are exactly normal to the surfaces. On the two circular sections the loads are exactly tangential. Since the total load is the same in all cases, the tangential load is evidently a maximum when the load is wholly tangential or when the section considered is the circular section.

It is possible to make geological applications of the theory of pure shear stated above provided that the reader will take for

[1]During the actual process of straining from a sphere to a given shear, even those material planes which are undisturbed at the end of the process undergo distortions, but these deformations are equal and opposite.

[2]This was first shown, I believe, in the paper already referred to, p. 37. I have given a neater proof in Amer. Jour. of Sci., Vol. XLVI., 1893, p. 339.

granted two or three propositions which have been proved elsewhere. It is a fact that a simple uniform pressure acting upon

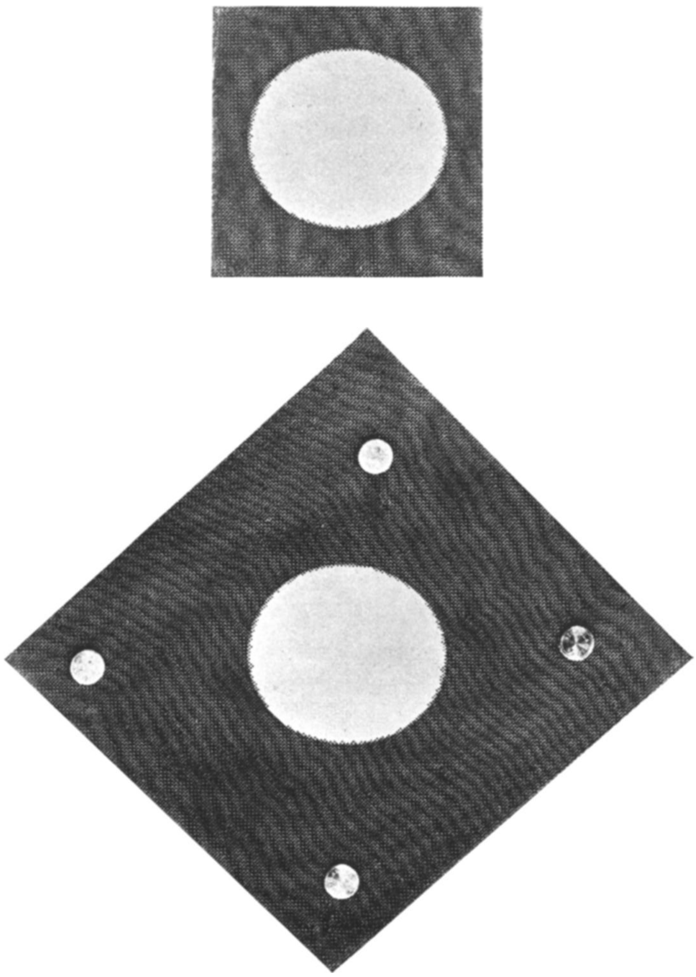

FIG. 2.—Shear illustrated by deformation of a circle drawn on wire netting.

a cube normally to two opposite faces is resoluble into forces which tend to produce[1] a cubical compression and two equal pure

[1] Exactly one-third of the total pressure is employed in producing each of these three elementary strains whether they are of finite or of infinitesimal amount.

shears at right angles to one another. The cubical compression does not tend to produce rupture or distortion, and each of the shears acts independently of the other. Hence in considering the effects of direct pressure upon rock, each shear must be considered by itself, and the effects combined. Were the resolution of forces not what it is, the consideration of pure shear would be almost valueless for geological purposes, because the combination of two exactly equal loads of opposite signs at exactly 90° unaccompanied by other forces must occur in nature only once in an infinite number of times.

If a cube of homogeneous matter is subjected to pure shearing strain it will be deformed gradually until its elastic limit is reached. With most solids analogous to rocks this amount of deformation is very small indeed, so that the shortening of the cube at this limit would not exceed one per cent. and might fall much short of it. For the purposes of this paper the distortion within the elastic limit can be neglected. Just above the elastic limit the mass will begin to undergo permanent deformation. So far as is known every substance whatever is capable of permanent deformation. Were this not true the exceptions to the statement would be perfectly elastic bodies.

The nature of permanent deformation in a pure shear is inferable from what has been stated in preceding paragraphs. It consists in the motion past one another of circular sections of the strain ellipsoid and the motion is such that although the continuity of the mass is not destroyed, relief from pressure does not restore the molecules to their original positions. This irreversible movement of particles along the circular planes of the shear ellipsoid is the simplest case of what Tresca called the *flow* of solids. It differs fundamentally from the flow of liquids, which takes place under corresponding circumstances in a direction perpendicular to the line of force, instead of at an angle somewhat exceeding 45° as is the case with solids. In ordinary solids under pure shearing stress flow begins at almost exactly 45° to the pressure; as the strain increases this angle increases but it can reach 90° only when the thickness of the mass is reduced to zero.

It is very easy to calculate and illustrate the position of the planes of gliding in a pure shear. If the unit cube is reduced by a pure shear to a height $\frac{1}{a}$ (or elongated at a right angle to this direction to a length a) then the tangent of the angle which the circular planes make with the greatest axis of the ellipsoid is $\frac{1}{a}$, which it is worth while to note is also the smallest semi-axis of the ellipsoid. If a differs insensibly from unity, the angle in question differs insensibly from 45°, and for the values $a = \frac{4}{3}$ 2, 4, the respective corresponding angles are to the nearest degree 37°, 27°, 14°.

By way of illustration, consider a cube of homogeneous matter subjected to pure shear such that its height is ultimately reduced to one-half and let the elastic limit be so small that flow sets in when deformation is very small. Then the first lines to flow will stand at 45° (sensibly) to the direction of greatest elongation while at the close of the experiment the last lines to flow will stand at 27° to this axis. The material surfaces on which flow first took place of course acquire greater and greater inclination as the deformation increases, but their position is determinable in any state of strain because they connect the diagonal corners of the strained cube.

This case is illustrated in Fig. 3. The broken lines in the distorted cube answer to the directions in which flow begins; the dotted lines are those along which flow takes place at the close of the operation; the short broken or dotted lines in the square representing the undistorted cube show the original positions of the two sets of lines before strain. For strains intermediate between the initial and final states the lines of flow are also intermediate in position.

For comparison with other strains the two wedges in the unstrained cube marked R and r are of much importance. Each of these wedges is bounded upon one side by the line of particles which are the first to undergo flow and on the other side by the last line of particles which undergo flow. In pure shear $R = r$.

One may regard the flow surfaces as mathematical planes (like the plane of the meridian) which occupy different positions relatively to the material particles as the mass undergoes increasing deformation.[1] That set of particles which at any instant coincides in direction with the flow planes undergoes deformation and no other particles are subject to gliding at that instant. The

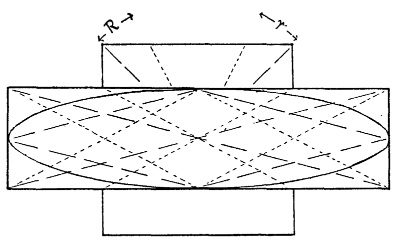

FIG. 3. Flow distribution in pure shear.

flow planes range through successive portions of the material cube and in pure shear they range through equal portions of the cube on each side of the line of pressure. It will be seen later that this is not the case in scission or in any strain into which scission enters as a component. In the illustration the range R or r in the unstrained solid is 18° and the corresponding surfaces in the strained mass make angles of nearly 13°.

The process outlined above must go on in any homogeneous solid substance which is not infinitely brittle when subjected to pure shear under conditions which preclude rupture; whether the mass is of lead or of quartz makes no difference in this respect.

It seems clear that flow in a solid must in some manner affect its resistance to rupture. It is conceivable that a body which had been strained beyond its elastic limit should split with *more* difficulty along the lines of flow or approximately at 45° to the line of force, than in any other direction. Experiment, however, shows that it splits with less difficulty in this direction. The

[1] Whatever the amount of a pure shear may be at any instant, the flow lines are parallel to lines passing through the intersections of the undisturbed cube with the distorted cube.

experimental side of the question will be touched upon later. Flow must cause molecular rearrangement even in chemically stable bodies. One may imagine flow to consist in the rolling over of molecules in alternate very thin layers and the effect being something like the lamellar twinning of feldspars. In such cases it would seem inevitable that the twinning planes should be planes of weakness. The energy of the strain is converted into heat and this heat is developed exclusively along the flow surfaces. In chemically unstable bodies this heat will manifest itself in the production of secondary minerals such as mica, and the new minerals will arrange themselves along the lines of flow. This action appears to me to constitute dynamo-metamorphism so far as such metamorphism attends direct pressure.

Taking it for granted that flow surfaces are surfaces of weakness rather than of increased strength, two distinguishable cases may arise in the progress of shear. It may happen (with some substances and under some relations between the active forces) that, although the direction of greatest tangential load passes away from the direction of initial flow, the diminished tangential load will still produce more motion on the weakened surfaces than in the unweakened but more heavily loaded surfaces. In such cases rupture will ensue at nearly 45°, the distortion will be insensible and the substance is a "brittle" one; or in other words, the difference between the elastic limit and the ultimate strength is exceedingly small. In the opposite case flow will cease on the initial planes and commence anew on the planes where the tangential load has risen to a maximum. Experimentally no absolutely brittle substances are known. There is always so far as known a range of pressure (usually a small one) within which flow occurs along successive surfaces so that considerable deformation without rupture can be affected.

If distortion by pure shear is carried very far without true rupture, the mass will be more or less cleavable in a number of directions separable into two systems. All the cleavages of either system will lie within a few degrees of one another. The consequence will be a somewhat confused foliation. It will be

possible to break out masses with very acute rhombic cross-sections which in the case illustrated in Fig. 3 would have angles of 13°, but such rhombs would themselves be cleavable into still more acute flakes. I should call such a mass a *schist* (whether crystalline or not), reserving the name *slate* for a more regular structure.[1] Sir Archibald Geikie distinguishes slate from schists calling slates "cleaved" and schists "foliated;" he makes approximately parallel lenticular and usually wavy layers or folia characteristic of the schists.[2] This definition seems to answer to my use of the term and to the explanation given above, but many geologists use the terms slate and schist almost interchangeably. In the interest of precision it is most desirable that slate and schist should be distinguished and that geologists should define the sense in which they employ these terms.

Passing now to the second strain to be discussed it will be well to state how scission is produced. The forces acting on any small cubical portion of a strained mass are reducible to three forces which are normal to faces of the cube, and a couple. If the mass is in equilibrium these forces and this couple are exactly balanced by the resistances which the mass itself opposes to strain. The normal forces produce changes of volume and pure shears such as have been discussed above. The effect of the couple is to produce the distortion here called a scission and more usually known as a "simple shear" or a "shearing motion," but never as pure shear. The origin of scission is thus different from that of pure shear. Because it arises from the action of a couple, it is called a rotational strain. Scission is quite as important as pure shear. It may be said to be present in practically all real strains because the absence of scission characterizes only a limiting case which is only approximately realizable even with refined apparatus.[3] Scission is not a strain which by itself

[1] There seems no logic in the constant employment of the term "crystalline" schists unless these are to be distinguished from other schists not crystalline.

[2] Text-book of Geol., 1893, p. 103.

[3] The pole about which the couple tends to produce rotation does not in general coincide with the direction of the maximum, minimum or mean normal stresses. One

is common in nature.[1] When this strain is pushed to the point of rupture it leads to a solitary fault. It is nearly the strain produced when a mass is being cut with shears, and it can be illustrated with a pack of cards. Scission is that strain in which the distance of any particle from two rectangular planes of reference is unchanged, while its distance from a third plane perpendicular to the two others is simply proportional to its distance from one of those others. Thus if x, y, z are the initial coördinates, x_1, y_1, z_1 the final coördinates of a point, and b a constant, $x = x_1$, $y, = y_1$, $z = z_1 b$ represents a scission. This is illustrated in Fig. 4, where $b = tan\,\theta$. This strain is not attended by a change of volume.

Instead of discussing the nature of rotational strains in general, I shall simply show how to trace a feature of scission which is in fact the effect of rotation. In scission, as in pure shear, the deformation is effected by the gliding of planes answering to the circular sections of the strain ellipsoid; but the range of these two sets of planes through the mass subjected to strain is not the same on each side of the line of pressure. In pure shear the two angles R and r are equal. In scission this is not the case; on the contrary r becomes zero and R gains what r has lost. When the mass has a low limit of elasticity the initial lines of flow will

may either define the couple by the three angles which its pole makes with the principal normal stresses or one may resolve it into three couples with poles coincident with the principal stresses.

The forces at a point are thus defined by six independent quantities, and thes- correspond to six independent resistances which are similar in character to the extere nal forces but not in general similarly oriented. The work done against elastic resistance during a small strain is a homogeneous quadratic function of these six quantities. Such a function contains thirty-six coefficients which reduce to twenty-one by identities. These are the "twenty-one elastic coefficients" of eolotropic matter which are very famous. They have even been celebrated in verse! If the elastic forces between two molecules are reducible to a single force acting between their centers of mass (a theory incorrectly ascribed to Boscovitch) the twenty-one coefficients reduce to fifteen; but this theory is not borne out in general by experiment though some substances, such as glass, closely fulfil its conditions.

Amorphous substances have two elastic constants and regular minerals have only three, but triclinic crystals boast the full number of twenty-one.

[1] Purely tangential force would expand itself close to the surface to which it was applied. Slickensides may be regarded as due to approximately pure scission.

be at sensibly 90° to one another and in scission as illustrated in Fig. 4 one of these directions will be horizontal, the other vertical. When the strain has become great the circular sections of the strain ellipsoid will no longer be at right angles. The angle between them is determinable in terms of the axes of the stress ellipse and (just as in pure shear) it is twice the angle whose

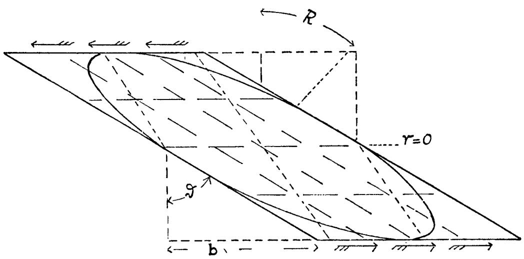

FIG. 4.—Flow distribution in scission.

tangent is the least axis of the ellipsoid. Now since lines parallel to the axis of x undergo no change of length, one of the sets of circular sections must coincide with this direction throughout the strain so that the angle r vanishes. Hence also if one compares a scission with a pure shear in which the ultimate ellipsoids are equal or in which the amounts of distortion are the same, the range of the second set of planes of circular section is just twice as great in scission as it is in pure shear. In dealing with real solids (which always possess viscosity), and finite strains, this difference between pure shear and scission is of great importance; but as scission alone is probably even rarer in nature than pure shear, it will be best to defer comment on this subject until the almost universal combination of pure shear and scission has been discussed.

An inclined force[1] acting on a supported cube would produce among its effects a pure shear and a scission in one plane.[2] It is

[1] The precise direction of a force which would produce a given shear and a given scission is too complex a subject for this paper.

[2] When the mass is homogeneous and symmetrically placed with reference to the forces, the other strains produced would be a second pure shear at right angles to the first and a dilatation. The two pure shears would act independently of one another.

sufficient here to consider as an example a shear and a scission giving equal distortions and simultaneously affecting the same cube. It is very easy to compute all the elements of this strain when for example each strain by itself is such as to increase by one-half the length of the elongated axis. The result is as follows: The length of the major axis would be almost exactly 2;

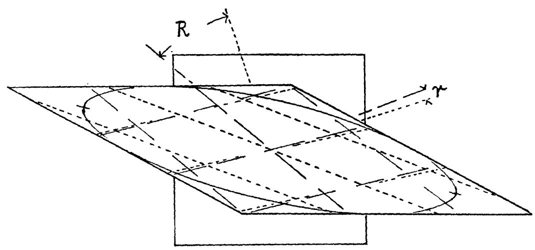

FIG. 5.—Flow distribution when shear and scission of equal amounts are combined.

and it would stand at an angle of —13° to *ox*. The angle between the final circular sections would be 53°. One of them would stand at 13½° to *ox* and the other at —39½°. The range of the lines of flow referred to the unstrained solid would be $r = 3°$ $27'$, $R = 33°$ $26'$.

In this case one set of planes of maximum tangential load ranges through ten times as great an angle as does the opposite set. To estimate the effects of this difference it is indispensable to consider the influence of viscosity. This subject has its difficulties, but there is nothing to prevent any attentive reader from acquiring the elementary acquaintance with it needful for the present purposes.

The resistances which a mass offers to distortion can be divided into two classes. One of these is independent of the time-rate at which the strain is produced and the other class is not independent of this rate. If both classes are considered it

If one of the shears is of ratio α and the other of ratio β the combination of the two would yield an ellipsoid with axes α, β and $\frac{1}{\alpha}\beta$. The β shear, though independent of the α shear would modify the final angle of the lines of flow due to the α shear by changing the vertical dimensions.

is manifest that all possible resistances are included. The independent class are the elastic resistances. The resistances which depend on the rate of straining are the viscous resistances. Examples of viscous resistance are seen in the rapid subsidence of vibration in a tuning fork. If steel were an ideal elastic solid, a fork in a vacuum would vibrate forever. If rubber were ideally elastic, a band supporting a weight and stretched so as to make the weight dance up and down would continue to stretch and contract indefinitely, while in reality the action ceases in two or three seconds. If a weight is suspended on a wire for a second, the wire may be practically unimpaired by the strain, when the same weight left for a minute would seriously elongate the wire. Flow in such a wire is a process which demands time; and therefore it involves viscosity. Such illustrations show that viscosity is not a merely recondite property of matter which can be relegated to theoretical physicists and neglected by geologists. It is absolûtely certain that it must play as important a part in geological deformation as the elastic forces. During an instant of time elastic and viscous resistance are indistinguishable and they coöperate with one another to resist deformation. When one considers a very long period of time instead of a very short one, viscous resistance almost disappears and it vanishes utterly when the time is infinite. It is easy to see that this must be true; for the intensity of resistances which continue to exist after an infinite time is independent of time. Hence, if any mass is strained for a short time its resistance is the sum of its elastic and viscous resistances. If it is strained for a long time, on the other hand, only the elastic resistances will oppose deformation. Again, if a body is strained for a brief period in one direction and for a long period in another, it will act as if it were strong in the former direction and relatively weak in the latter.

In scission the sheets of the mass parallel to the fixed support are constantly impelled to glide over one another by the maximum tangential load and if the forces act for a long time the flow in this direction is opposed only by the elastic resistance. In the other set of planes of maximum tangential load in

a scission this load is at each instant applied to a new set of particles, which offer not only elastic resistance but viscous resistance as well; they are practically and actually stronger for this coöperation. Now suppose that the load has just reached the limit at which flow can take place in the horizontal planes; then this load must necessarily be insufficient to produce flow on the inclined planes. Hence. if flow produces structure at all, such a mass will show structure in one direction and in one direction only.

In the case of combined scission and shear illustrated in Fig. 5, the same principles apply. The fibers forming the wedge r are subjected to maximum tangential strain ten times as long as are the corresponding fibers in the wedge R. Hence those in the larger wedge offer greater effective resistance to flow than those in the smaller wedge and the pressure might be so adjusted as to render the mass cleavable only in the direction of r. The difference between R and r exists whenever scission forms an element in the strain or whenever there is a couple acting at the point considered.

At first sight this result seems almost too sweeping. It might seem to imply that double structure should be very rare which it certainly is not. This small difficulty is readily explained; for in any substance with a moderately large difference between the elastic limit and the ultimate strength, shear and scission may be so combined that flow without rupture will take place on both sets of planes though faster on one set than on the other. The very rare instances are those in which the two structures are equally well developed indicating pure shear.[1]

In my opinion then true slate, cleavable in directions so nearly parallel that no considerable divergence appears, is due to

[1] The limits of this paper preclude the explanation of a variety of structures arising from minor modifications of dynamic conditions. Flow on one set of planes may be accompanied by sharp joints on the conjugate surfaces. Such are the master joints in slate. When the force is rapidly applied, or when the mass is very brittle or when the lateral support is insufficient, two sets of joints (each with its own spacing) may result. One such set of joints may be suppressed by the action of viscosity.

When deformation in two planes at right angles to one another is considered, two

rotational strains in which scission forms a component. These strains are due to external pressures, always inclined to the normal to the plane of cleavage, and the reason why only one set of cleavages makes its appearance in slate is that viscous resistance in the conceivable second set has prevented flow.

It appears to me possible to avoid this conclusion only by denying either that rocks undergo solid flow or that flow produces cleavage. No geologist will think of denying that rocks flow. The evidences of it are too numerous to be worth mentioning. The mechanical conditions are also well understood. Solid flow without rupture will hardly take place unless there is some lateral obstruction to deformation as well as external pressure. The effect of the lateral confinement is to convert part of the pressure into more cubical compression; consequently the forces producing shears and scissions rise very slowly with increase of external pressure. Under such conditions the deforming stresses may for a long time be kept close to the elastic limit and an infinite amount of flow may be produced in any substance not ideally brittle. The conditions appropriate to flow must be more prevalent at great depths then at small ones, but they cannot be confined to great depths.

That flow really produces cleavage seems to me demonstrated by experiments on solids such as iron. There is evidence that red-hot bar iron or steel is a true solid, and it is known that manufactured bar iron is fibrous and cleavable. This is especially well brought out in experiments on iron plates with high explosives. Even if hot iron were no true solid, the way in which

conjugate systems of cleavages or joints may appear in each, and any one of these four systems may be suppressed by the action of viscosity. One of the shears may fail to act on account of lateral resistance, thus a rock may show 4, 3, 2 or 1 sets of structures due to the same force.

The spacing of fissures is an interesting topic very important in mining districts. My theory is that fissures will so form as to afford the greatest relief by pressure per square foot of rupture. This leads to a definite distribution of faults in homogeneously strained rock.

Tension will not produce joints or cleavages. The theory of the distribution of tension cracks is the explanation of columnar structure.

rail heads are rendered schistose near railway stations by the arrest of moving trains would show the action. In drawing wire similar phenomena appear and in both cases the direction of cleavage is that of flow. Experiments on semi-solids such as pastry and clay are less satisfactory inasmuch as the presence of fluids must disturb the purity of the results, yet in so far as their behavior differs from the known behavior of true fluids, they are instructive. Such experiments when carefully scrutinized yield results compatible with the theory of this paper.

That flow with attendant weakening of cohesion is the origin of slaty cleavage appears to have been recognized by the first investigator to offer a mechanical explanation of this structure. John Phillips in 1843 ascribed cleavage to a "creeping movement among the particles of the rock, the effect of which was to roll them forward." Mr. Daubrée says that schistose or laminated structure is a direct consequence of gliding (glissement), a term which he explains by the remark that the different velocities acquired by contiguous molecules make them glide past one another.[1] Actual cases are on record in which evidences of diminished cohesion (without rupture) make their appearance in rocks in directions parallel to faulted joints. Professor Judd has described such,[2] and they clearly show that flow takes place as a preliminary to jointing and in the less strained portions of jointed rocks.

The deformation of crystals on "gliding planes" which is usually accompanied by secondary twinning is a case of flow in eolotropic masses. The gliding planes also become after relative movement planes of easy cleavage, not in general identical in direction with the inherent cleavage planes of undeformed crystals. The gliding planes in the case of calcite seem to have been known to Huyghens and they have been studied in a great many minerals during the last few decades. Professor Judd has produced gliding planes in quartz by means of pressure, and it is probable that the cleavage which is produced in quartz by alter-

[1] Bull. Soc. Géol. de France, Vol. 4, 1876, p. 541.

[2] Mineralogical Mag., Vol. 7, 1886, p. 81.

nate heating and cooling is due to the flow on such planes.[1] Several mineralogists have also come to the conclusion that the twinning of minerals in nature is largely due to the strain they have undergone. This idea appears to have been suggested in the first instance by Mr. Max Baur in 1878.[2] In massive rocks the minerals are usually strained as a result of cooling and there is much evidence from independent observers[3] that the polysynthetic structures of feldspars and pyroxenes in rocks are wholly or in part due to these strains.

In view of the evidence merely outlined above it appears to me utterly impossible to deny that solid flow does as a matter of fact induce a true cleavage which is parallel to the lines of relative tangential motion or gliding, this cleavage not necessarily being accompanied by any actual ruptures however microscopic. It appears also that this action goes on in thoroughly homogeneous substances such as calcite and quartz. These minerals are not indeed amorphous, but that fact only modifies the direction in which flow will occur most readily, not the principles governing flow. The schistosity of deformed quartz, calcite, feldspar and rock salt crystals cannot possibly depend on the flattening or rotation of included particles.

The theory of slaty cleavage held by most geologists ascribes the structure to the flattening of particles at right angles to the line of pressure and the rotation of mica scales towards the same position. There are some objections to this view. In the first place only the exceptional irrotational strains produce flattening at right angles to the line of force so that, even if fissility were produced by flattening, it would be a mistake to infer that the direction of force was normal to the cleavage.[4] In the second place this theory assumes either that the flattened particles resist fracture more persistently than the matrix in which they are

[1] *Ibid.*, Vol. 8, 1888, p. 1 and Vol. 10, 1892, p. 123.

[2] Zeitsch. der D. Geol. Ges., Vol. 30, 1878, p. 323.

[3] O. Mugge, L. van Werweke, Judd, etc.

[4] In all rotational strains the inclination of the greatest axis of the ellipsoid varies with the amount of strain. It therefore changes during strain when the direction of the force is fixed.

imbedded, or that the flattened particles themselves are cleavable parallel to their greatest extension. If one supposes the material from which slate is made to be a soft mud containing minute sand grains, it seems plausible to assume that in indurated slate also the matrix is weaker than the enclosed particles. But in the analogous dynamo-metamorphosed conglomerates the matrix is often firmer than the pebbles and there is no reason to suppose than this characteristic is not shared by the fine-grained masses. In such cases no cleavage could result from flattening unless the larger grains are cleavable in one direction. This could scarcely happen unless they were mainly mica scales and I do not think that true cleavage would result even in that case. It does not appear to me that any closer approach could be made to slaty cleavage by flattening the particles, even in a weak matrix, than is presented in natural sandstones; for in these also the mica scales and thin particles of quartz are in the great majority of cases parallel to the bedding. Now it is true that two beds of sandstone often split apart from one another with some readiness though the fractured surfaces do not resemble those of slate. This, however, is not in point. If one tries to split a portion of a single, uniform bed of sandstone, it requires careful observation to detect greater facility of cleavage in one direction than another. Thus the mere fact of parallel orientation does not necessarily lead to slaty cleavage.

Tyndall's experiment on wax seems well suited to decide between the old and new theories. It is also one suitable for performance by students.[1] If the flattening theory is correct, compressed cakes should split entirely across, and at least as well at the center as at the edges. If on the contrary I have correctly elucidated the problem there should be a small central core to each compressed cake unaffected by cleavage. For my

[1] In my former discussion, p. 81, I have given some notes on the methods of procedure in this experiment. Tyndall's paper is printed in Phil. Mag., Vol. 12, 1856, p. 37. The horizontal friction between the wax and the rigid surfaces pressing upon it, when combined with the direct pressure, gives an inclined resultant and strains which are rotational excepting along the central vertical line of the wax cake.

part I never could succeed in getting slaty structure at the cores of the fissile mass.

In the interest of geology and of active geologists it is most desirable that a decision as to the origin and nature of slaty cleavage should be reached as soon as possible, and I am in hopes that this sketch of my theory may at least promote discussion of the whole subject. GEORGE F. BECKER.

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